Negative differential Rashba effect in two-dimensional hole systems

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We demonstrate experimentally and theoretically that two-dimensional (2D) heavy hole systems in single heterostructures exhibit a *decrease* in spin-orbit interaction-induced spin splitting with an increase in perpendicular electric field. Using front and back gates, we measure the spin splitting as a function of applied electric field while keeping the density constant. Our results are in contrast to the more familiar case of 2D electrons where spin splitting increases with electric field.

In a solid that lacks inversion symmetry, the spin-orbit interaction leads to a lifting of the spin degeneracy of the energy bands, even in the absence of an applied magnetic field, B. In such a solid, the energy bands at finite wave vectors are split into two spin subbands with different energy surfaces, populations, and effective masses. The problem of inversion asymmetry-induced spin splitting in two-dimensional (2D) carrier systems in semiconductor heterojunctions and quantum wells [1, 2, 3, 4] has become of renewed interest recently [5] because of their possible use in realizing spintronic devices such as a spin field-effect transistor [6, 7], and for studying fundamental phenomena such as the spin Berry phase [8, 9].

In 2D carrier systems confined to GaAs/AlGaAs heterostructures, the bulk inversion asymmetry (BIA) of the zinc blende structure and the structure inversion asymmetry (SIA) of the confining potential contribute to the $B = 0$ spin splitting [4, 5]. While BIA is fixed, the so called Rashba spin splitting [10] due to SIA can be tuned by means of external gates that change the perpendicular electric field ($E_\perp$) in the sample. For many years it has been assumed that the Rashba spin splitting in 2D carrier systems is proportional to $E_\perp$ that characterizes the inversion asymmetry of the confining potential [4]. 2D holes contained in a GaAs *square* quantum well provide an example [11]. On the contrary, in the present work we show both experimentally and theoretically that for heavy holes confined to a *triangular* well at the GaAs/AlGaAs interface, spin splitting *decreases* with an increase in $E_\perp$. We demonstrate this negative differential Rashba effect by analyzing the Shubnikov-de Haas oscillations in this system at a constant density. We note that hole systems have recently gained great attention for spintronics applications [12] because ferromagnetic (III,Mn)V compounds are intrinsically p type. A detailed understanding of the $B = 0$ spin splitting in hole systems is thus of great importance.

The sample used in our study was grown on a GaAs (001) substrate by molecular beam epitaxy and contains a modulation-doped 2D hole system confined to a GaAs/AlGaAs heterostructure [Fig. 1(a)]. The $Al_{0.3}Ga_{0.7}As$/GaAs interface is separated from a 16 nm thick Be-doped $Al_{0.3}Ga_{0.7}As$ layer (Be concentration of

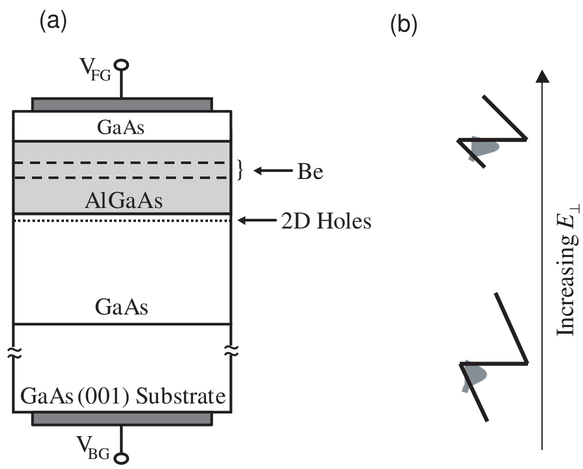

FIG. 1: (a) Schematic sample cross section. (b) Schematic demonstrating how the gate voltages change the shape of the 2D heterostructure potential (lines) and the charge density profile (shaded) while keeping the density constant.

3.5×10^{18} cm^{-3}) by a 25 nm $Al_{0.3}Ga_{0.7}As$ spacer layer. We fabricated Hall bar samples via lithography and used In/Zn alloyed at 440°C for the ohmic contacts. Metal gates were deposited on the sample's front and back to control the 2D hole density (p) and $E_\perp$. The low temperature mobility for the sample is 7.7×10^4 cm^2/Vs at $p = 2.3 \times 10^{11}$ cm^{-2}. We measured the longitudinal (R_{xx}) and transverse (R_{xy}) magneto-resistances at $T \approx 30$ mK via a standard low frequency lock-in technique.

In single heterostructures, where SIA is the dominant source of spin splitting, the electric field $E_\perp$ experienced by the carriers is determined by the density-dependent self-consistent potential. This potential is determined, in turn, by the sample structure (spacer layer thickness and doping, etc.), and the applied gate biases. In our measurements, we used front and back gate biases to change the potential's profile and hence $E_\perp$ [Fig. 1(b)], while keeping the density constant. We initially set the front-gate voltage (V_{FG}) to 0.55 V and back-gate voltage (V_{BG}) to -100 V with respect to the 2D hole system, leading to $p = 1.84 \times 10^{11}$ cm^{-2}, and measured R_{xy} and R_{xx} as a function of B between -3 T to 5 T. Then at $B = 1$ T, we

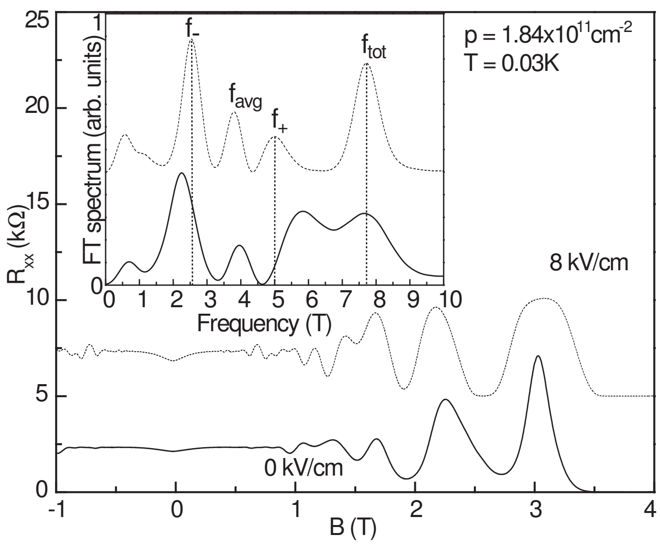

FIG. 2: Observed Shubnikov-de Haas oscillations for a 2D hole system confined to a (001) GaAs/AlGaAs single heterstructure at two different $E_\perp$. Inset: The Fourier spectra of these oscillations at the corresponding electric fields. The dotted curves in the main figure and the inset are shifted vertically for clarity.

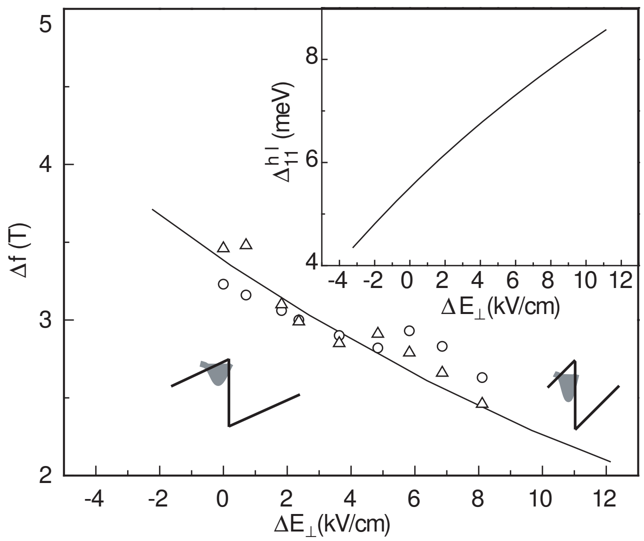

FIG. 3: Spin splitting, Δf, versus the change $\Delta E_\perp$ in the perpendicular electric field for the measured (o $= f_{\rm tot} - 2f_-$, $\triangle = f_+ - f_-$) and calculated (solid line) magneto-oscillations. The effect of varying $E_\perp$ on the shape of the 2D heterostructure potential (lines) and the charge density profile (shaded) is also shown. Inset: The increase in the energy gap Δ_{11}^{hl} between the first HH and LH subbands is shown.

increased $V_{\rm BG}$ and noted the change in R_{xy}; this change in R_{xy} gives the corresponding change in density (Δp). $V_{\rm FG}$ was then decreased to recover the original R_{xy} and hence the original p. This procedure leads to a change $\Delta E_\perp = e\Delta p/\epsilon$ in $E_\perp$ (e is the electron charge and ϵ is the dielectric constant) while keeping the density constant to within 1%. $\Delta E_\perp$ is measured with respect to $E_\perp$ at $V_{\rm FG} = 0.55$ V and $V_{\rm BG} = -100$ V.

Figure 2 shows the low-field Shubnikov-de Haas (SdH) oscillations for two $E_\perp$ differing by 8 kV/cm. The Fourier transform (FT) spectra of these oscillations, shown in Fig. 2 (inset), exhibit four dominant peaks at frequencies f_-, $f_{\rm avg}$, f_+, and $f_{\rm tot}$, with the relation $f_{\rm tot} = f_+ + f_- = 2f_{\rm avg}$. The $f_{\rm tot}$ frequency, when multiplied by e/h, matches well the total 2D hole density deduced from the Hall resistance (h is the Planck's constant). The two peaks at f_- and f_+ correspond to the holes in individual spin subbands although their positions times e/h do not exactly give the spin subband densities [5, 13, 14]. Nevertheless, as discussed below, this discrepancy between $(e/h)f_\pm$ and the $B = 0$ spin subband densities is minor and $\Delta f = f_+ - f_- = f_{\rm tot} - 2f_-$ provides a good measure of the spin splitting. The vertical lines in the inset of Fig. 2 at the f_- and f_+ peaks clearly indicate that Δf *decreases* when $\Delta E_\perp$ is increased from 0 to 8 kV/cm. The vertical line at the $f_{\rm tot}$ peak shows that the total hole density is held constant.

We compare the experimental data with accurate numerical calculations of the magneto-oscillations at $B > 0$. First we perform fully self-consistent calculations of the subband structure at $B = 0$ in order to obtain the Hartree potential $V_{\rm H}$ as a function of $E_\perp$ [15]. We assumed that the concentration of unintentional background impurities in the GaAs space charge layer was 1×10^{14} cm^{-3} [17]. This assumption is based on our sample parameters; we note, however, that the deduced spin splitting is insensitive to the exact value of the background doping. Using $V_{\rm H}$ we obtain the Landau fan chart for $B > 0$ from an 8×8 $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian that fully takes into account the spin-orbit coupling due to both SIA and BIA [5, 16]. From this fan chart we then determine the magneto-oscillations by evaluating the density of states at the Fermi energy as a function of B.

In Fig. 3 the experimental and calculated Δf from the corresponding FT spectra are plotted versus $\Delta E_\perp$. It is clear that increasing $E_\perp$ lowers the spin splitting [18]. We also verified that the calculated $B = 0$ spin splitting, defined as the difference between the spin subband densities, shows the same negative differential Rashba effect as Δf obtained from the calculated magneto-oscillations. The difference between the $B = 0$ spin splitting times h/e and Δf is only $\lesssim 0.14$ T in the range of $E_\perp$ shown in Fig. 3. This confirms that the $B = 0$ spin splitting shows the same negative differential trend.

We can understand these surprising results in the following way. The hole states in the uppermost valence band Γ_8^v have the angular momentum $j = 3/2$. In 2D systems, the four hole states split into heavy-hole (HH) states with z component of angular momentum $m = \pm 3/2$ and light-hole (LH) states with $m = \pm 1/2$. Here the quantization axis is perpendicular to the 2D

plane. On the other hand, the Rashba spin-orbit coupling acts like a $\boldsymbol{k}$-dependent effective magnetic field which is oriented in the plane so that it favors to orient the quantization axis of the angular momentum in-plane. However, this is not possible within the subspace of HH states ($m = \pm 3/2$) so that — in contrast to $j = 1/2$ electron systems — the Rashba spin splitting of HH states is a higher-order effect. Neglecting anisotropic corrections, it is characterized by the Hamiltonian [5]

$$H^h_{\mathrm{SO}} = \beta^h_1 \, E_\perp \, i \, (k^3_+ \sigma_- - k^3_- \sigma_+), \tag{1}$$

with $\sigma_\pm = 1/2(\sigma_x \pm i\sigma_y)$ and $k_\pm = k_x \pm ik_y$, where σ_x and σ_y are the Pauli spin matrices in the x and y directions respectively. Using third-order Löwdin perturbation theory [5] we obtain for the Rashba coefficient β^h_α of the lowest HH subband $\alpha = 1$

$$\beta^h_1 = a \, \gamma_3 (\gamma_2 + \gamma_3) \, \frac{e\hbar^4}{m_0^2} \left[\frac{1}{\Delta^{hl}_{11}} \left(\frac{1}{\Delta^{hl}_{12}} - \frac{1}{\Delta^{hh}_{12}} \right) + \frac{1}{\Delta^{hl}_{12} \, \Delta^{hh}_{12}} \right], \tag{2}$$

where γ_2 and γ_3 are the Luttinger parameters [16] and $\Delta^{\nu\nu'}_{\alpha\alpha'} \equiv \mathcal{E}^\nu_\alpha - \mathcal{E}^{\nu'}_{\alpha'}$ where $\mathcal{E}^h_\alpha$ and $\mathcal{E}^l_\alpha$ are the energies of the αth HH and LH subband, respectively. The symbol a denotes a numerical prefactor which depends on the geometry of the quasi-2D system. We can estimate the value of a assuming an infinitely deep rectangular quantum well which yields $a = 64/(9\pi^2)$. We see from Eq. (2) that the Rashba spin splitting of the HH states depends not only on the electric field $E_\perp$ but also on the separation between the HH and LH subbands. As can be seen in Fig. 3 (inset), the gap between the HH-LH subbands increases with an increase in $E_\perp$, giving rise to a decreasing Rashba coefficient β^h_1. This result reflects the fact that a large HH-LH splitting yields a "rigid" angular momentum perpendicular to the 2D plane so that the Rashba spin splitting will be suppressed.

We can estimate the effect of changing $E_\perp$ using the well-known triangular potential approximation [19]. Here we have, for the subband energies $\mathcal{E}^\nu_\alpha$ measured from the valence band edge, $\mathcal{E}^\nu_\alpha \propto E_\perp^{2/3}$ which implies $\beta^h_\alpha \propto E_\perp^{-4/3}$. Therefore, we can expect from Eqs. (1) and (2) that the Rashba spin splitting *decreases* proportional to $E_\perp^{-1/3}$ when $E_\perp$ is increased, in agreement with our more accurate numerical calculations.

In a previous study [20] this surprising behavior of $\beta^h_1 E_\perp$ was shown as a function of density. By lowering the density, spin splitting and $E_\perp$ both decrease but the term $\beta^h_1 E_\perp$ increases. However in the present work, by keeping the density constant and only varying $E_\perp$, we are able to directly demonstrate the negative differential Rashba effect in heavy hole 2D systems confined to single GaAs/AlGaAs heterostructures.

In conclusion, our study highlights the subtle and unexpected dependence of the Rashba spin splitting on $E_\perp$ in 2D hole systems. The results are important for the spintronic devices [6, 7, 12] whose operation relies on the tuning of the spin splitting via applied electric field.

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